

A BINARY QUANTIZER
WITH A RESOLUTION OF ONE PART IN A THOUSAND

by

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ABSTRACT

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A logical design for a binary quantizer with a resolution of one part in one thousand and a sampling rate of one thousand times per second has been developed. The proposed system is all electronic and may be classified as a $2^{n/2+1}$ -step device as contrasted with the more common n -step and 2^n -step quantizers.

The design developed employs a voltage comparator to transform the voltage to be coded into a time interval. A certain number of fixed time intervals are subtracted from the main interval and the remainder is essentially multiplied by 32. The intervals subtracted and the multiplied remainder are used to activate gate circuits which gate pulses into a binary counter.

In evolving the design for a circuit to meet the specifications chosen, emphasis was placed on the development of those parts of the circuit which had not been sufficiently developed for application to this problem. In particular, development work has been carried out on a voltage comparator to definitely establish that a resolution of one part in a thousand is possible. Also, a circuit has been designed to transform a variable time interval of 0-12 microseconds into a gate pulse width 32 times as long to an accuracy sufficient for use in the proposed system of quantization.

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Section I

Introduction

1.0 Objective:

The object of this thesis has been to evolve a logical design for a device to quantize continuously varying information available as a voltage into a binary code representing the instantaneous amplitude at equally spaced intervals of time. The sampling rate was chosen to be a thousand times per second and the resolution to be sought was set at one part in a thousand. These specifications represent a reasonable extrapolation of present achievements in the field.

In evolving the design of a circuit to meet these specifications emphasis has been placed on the development of those parts of the circuit which had not been sufficiently developed for application to this problem. In particular, development work was carried out on a voltage comparator to definitely establish that a resolution of one part in a thousand is possible. Also, a circuit has been designed to transform a variable interval of time of 0-12 microseconds into a gate pulse width 32 times as long to an accuracy sufficient for use in the quantizer.

1.1 Theory of Quantization and Background:

In general, functions representing physical quantities such as temperature, pressure, velocity, etc., are continuously variable and

may be represented by an analogously varying electrical quantity. It is often desirable to operate upon such analogue quantities using digital techniques which require that the data be expressed in some code representing uniquely its amplitude at certain discrete intervals of time. Most commonly the code is a binary number and the intervals between samples are equal. It is generally desirable to sample and code as frequently as possible and to have a large number of codes so that the quantized steps are small. This gives the most accurate numerical representation of the continuous function. The accuracy or resolution of coding is seen to be the reciprocal of the highest number of unique codes possible.

For a maximum binary count of 2^n , n binary digits are used. It follows that ten binary digits are necessary to obtain a maximum of 1000 unique codes as is desired here.

There are several methods of quantization used in current practice. Perhaps the simplest is straightforward counting in the time domain. A voltage directly proportional to the instantaneous count is compared to the voltage representing the function to be coded. The number of counts completed by the time of coincidence is a measure of the value of the function at the time of coincidence. This is the so-called " 2^n -step" type of coding since a maximum of 2^n counts may be required in one sampling period. The associated digit register in which the binary number is developed will be subjected to a maximum of 2^n changes of state in the 2^n -step coder. Since the frequency of counting is limited, the frequency of sampling is limited. Resolution depends upon the accuracy of the coincidence detector.

Systems classified as n-step have been built with an accuracy of one part in 32 at MIT.^{1*} This type of device builds up a reference voltage by means of an n digit binary register in n steps. The reference voltage is compared with the function to be coded at each step and the polarity of the difference determines the succeeding step so as to get a better approximation to the function. This method involves decoding the binary number at each step for comparison. Its accuracy is dependent upon the accuracy of both decoding and comparison.

An n-step device to code in what may be termed the space domain has been developed by the Bell Telephone Laboratories.² This system employs a complicated and expensive circuit employing a special cathode ray tube to code to one part in 128. The resolution here depends upon the spacial resolution of the cross section of an electron beam at the face of the cathode ray tube.

Bibliographic research has revealed no published claims for an accuracy of greater than one part in 256 for a purely electronic system. An electro-mechanical system having a resolution of one part in 512 has been developed by the Signal Corps of the U.S. Army at the Fort Monmouth Laboratory. This system employs a positional servo-mechanism in its operation and so is limited to only a few independent samples per second.

At the sampling rate desired, 1000 times per second, only purely electronic methods appear to be feasible. The number of "steps"

* Numerical superscripts refer to numbered references in the bibliography.

inherent in the operation of any particular coding device is of importance because each step requires one or more switching actions in the electronic circuit. The switching transient limits the frequency of switching in any physically realizable circuit. It would appear that this limits the sampling rate of the 2^n -step coder much more than it does the sampling rate of the n -step coder, but consideration must be taken of the fact that each step in the case of the n -step device involves many switching actions whereas few are required for each step in the case of the 2^n -step device. If an n -step system were designed employing as many as 10 binary digits, however, it would in all probability have a higher sampling rate.

The 2^n -step coder uses simpler, more completely developed circuits than current n -step devices. Its accuracy depends principally upon the sensitivity and stability of the voltage comparison device used. The n -step coder requires both comparison and decoder circuits with equally high resolutions. The proposed system may be classified as a $2^{n/2+1}$ -step coder. Its accuracy depends upon the resolution of a voltage comparator as in the case of 2^n -step coder to which it bears a close kinship. For the same resolution, however, it is expected that the sampling rate of the proposed system will be greater.

How the two systems will ultimately compare depends upon development in the field of high speed counters in the case of the 2^n -step coder and upon development of precisely gated sweep generators in the case of the $2^{n/2+1}$ -step coder proposed. For the present, both systems are limited by the capabilities of present day voltage comparators.

Section II

The Proposed System

2.0 Theory of operation:

Basically, the voltage to be coded is converted into a time interval proportional to the instantaneous voltage amplitude to an accuracy of better than one part in a thousand. Pulses are generated at such a rate that exactly 32 pulses represent the maximum value of the function. These pulses are gated by the aforementioned time interval and applied to a binary count register of five binary digits which stores the so-called "coarse count". The time interval between the last coarse count gated and the end of the gating interval is effectively multiplied by 32 and used to gate succeeding pulses from the same source. This so-called "fine count" is applied to another part of the binary register and held. If now the coarse count is multiplied by 32 and added to the fine count it is seen that the function has been quantized into 1024 parts since each of the 32 coarse intervals has been broken up into 32 equal parts.

In the work described here the interval between the end of the coarse gating interval and the next succeeding coarse count pulse is multiplied in duration and used to gate a fine count. This count is then subtracted from 32 in effect to give the true fine count. This subtraction is accomplished in binary form by subtracting one fine

pulse and then taking the 32's complement of the result. To illustrate this, suppose the end of the coarse gating interval occurred $15/32$ of the distance between two coarse count pulses. Then 17 fine pulses would be gated and one of these subtracted leaving 16 which is represented by the binary number 10000. The 32's complement of this binary number is 01111 which represents 15, the actual fine count desired. The process of subtracting 1 is actually carried out in the time multiplier and the complement is automatically taken in the binary count register by the simple expedient of taking the count out of the register from the appropriate plate circuits of the flip-flops.

If the coarse count binary register is arranged so that it comprises the five highest binary digits of a ten digit register with the fine count register comprising the five lower digits, the coarse count is automatically multiplied by 32 and the entire count appears in the ten digit register taken as a whole.

2.1 The Block Diagram:

The process can be made more clear by considering the block diagram step by step in conjunction with typical waveforms (Fig. 1.). The Clock Pulse Generator supplies both a master timing pulse every 996 microseconds and the coarse and fine count pulses every 12 microseconds. ^{12 x 83} The master timing pulse starts the Main Sweep Generator and turns on the Coarse Count Gate which allows 12 microsecond pulses to enter the Course Count Register. The Main Sweep Generator generates a sweep which rises 102.4 volts in 32 coarse counts or 384 microseconds. This sweep is fed into the Comparator where it is compared

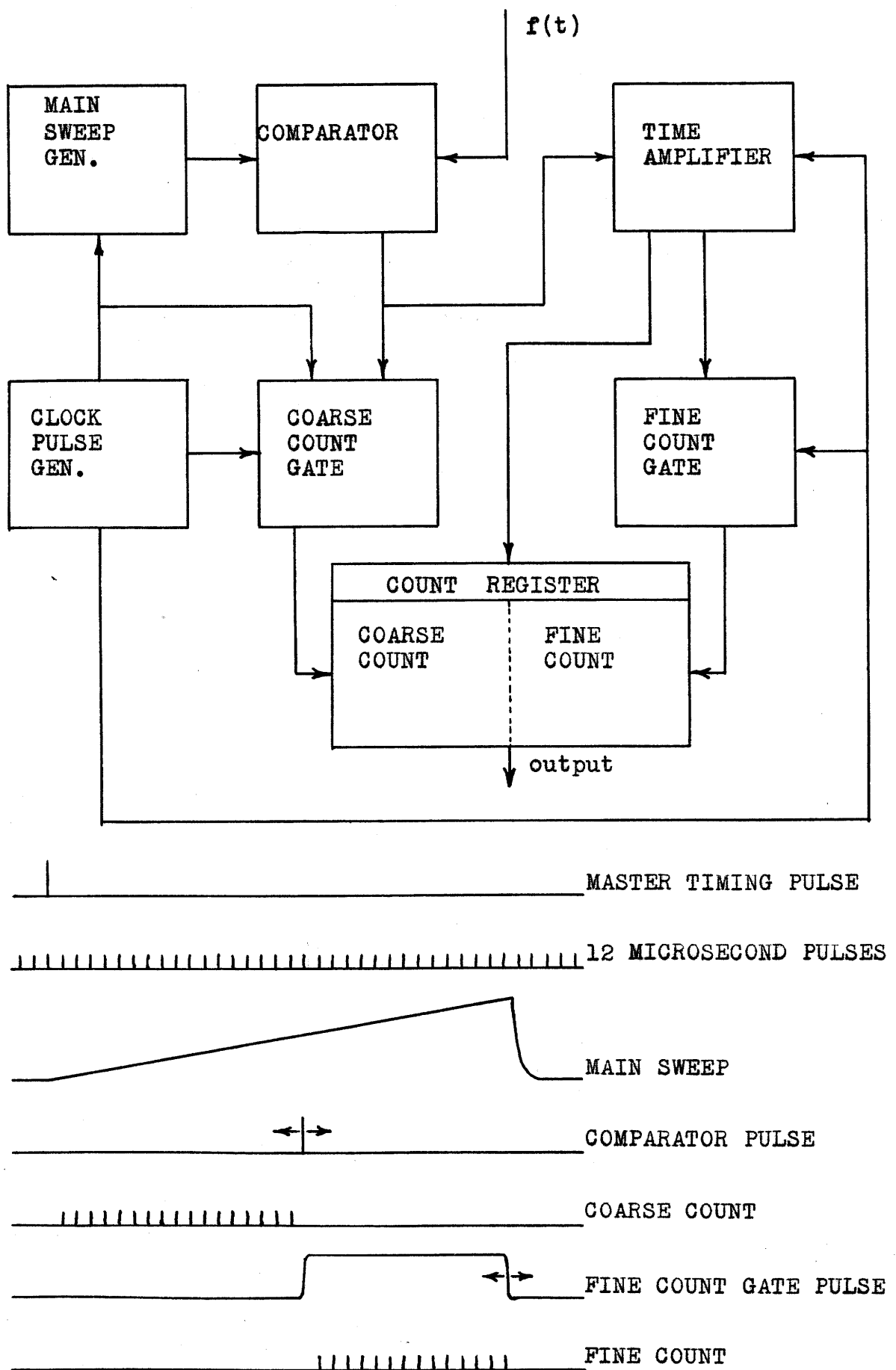


Fig. 1. QUANTIZER BLOCK DIAGRAM

with the function to be coded which is adjusted to have a maximum range of 102.4 volts. At the time of equality (within 0.1 volt) the Comparator delivers a pulse which turns off the Coarse Count Gate stopping the feed of 12 microsecond pulses into the Coarse Count Register. This pulse also activates the Time Amplifier which measures the time interval from then until the next 12 microsecond pulse. The Time Amplifier multiplies this time by 32 and subtracts 12 microseconds, delivering a gating pulse to the Fine Count Gate which gates 12 microsecond pulses into the Fine Count Register. It also feeds a read-out and reset signal to the Count Register at the end of the Fine Count Gate pulse.

It can be seen that the maximum number of counts used will be 64, taking 768 microseconds of the sampling interval and leaving 228 microseconds recovery time as a minimum.

2.2 Circuit Requirements:

We may now take each block individually, considering the operations it is to perform and the restrictions of stability and precision that must be imposed upon it if the quantizer as a whole is to meet the specifications of resolution and sampling time previously decided upon.

1. Clock Pulse Generator.

It is extremely important that the Clock Pulse Generator deliver pulses that do not vary in time with respect to each other by more than about .05 microseconds. The interval between pulses does not necessarily have to be an accurate 12 microseconds as long as the rest of the circuit is calibrated for the actual interval. The master timing pulse

must occur coincident with one of the 12 microsecond pulses, and must recur at some multiple of 12 microseconds such that the master timing pulses will be spaced approximately 1000 microseconds apart. The pulses must have a rise time of the order of .05 microseconds and a duration not to exceed 0.3 microseconds. The master timing pulse may have a longer duration but the rise time must be the same as for the 12 microsecond pulses.

These requirements are fairly easily met with present day pulse generating equipment using a crystal oscillator as a timing mechanism.³ For this reason it is not deemed necessary to concentrate effort in this direction.

ii. Main Sweep Generator.

The Main Sweep Generator must deliver a sawtooth which is linear to better than 0.1% of full scale and which is triggered on with a delay of less than 0.3 microseconds in starting. Furthermore, the starting voltage may not drift as much as 0.1% of maximum sweep voltage with respect to the zero reference of the input function. The full scale sweep has been arbitrarily set at 102.4 volts for this application.

A great deal of development has been applied to sweep and integrator circuits and a high state of perfection has been achieved.⁴ It is possible to use circuits commercially available for this component of the quantizer.

iii. Comparator:

This circuit will have a positive or negative sweep

voltage with amplitude 102.4 volts applied for comparison with a relatively fixed input signal. For the time being we shall consider the input signal held at a fixed voltage for a sampling interval so that it may be considered a constant. The comparator must indicate the instant of coincidence to within a fine count interval which is .375 microseconds. Alternatively, it must recognize equality of the voltages applied to better than 0.1 volt. Any fixed "delays" in either voltage or time may be calibrated out and the output pulse need not have stringent requirements for rise time or duration.

Many comparison circuits of various types have been designed, but bibliographic research reveals none which meets the exacting requirements listed above. For this reason a large part of the development work done in this thesis has been concerned with the design, test, and analysis of a voltage comparator. This is fully covered in section III which is devoted to the Comparator.

iv. Time Amplifier:

The Time Amplifier circuit must be capable of measuring a time interval of from 0 to 12 microseconds, and of producing a pulse which is 12 microseconds less than 32 times as long. In short, it must have a characteristic described by the following equation:

$$T_0 = 32T_1 - 12 \text{ microseconds.}$$

This must be done to a precision of better than one part in

32. This means, in the case of the input interval, that measurement must be made to within plus or minus .18 microseconds and that the output pulse must be within plus or minus 6 microseconds of the correct value.

Since this is a specialized circuit, and furthermore contains most of the non-conventional circuitry connected with the quantizer, a large part of the development work was concentrated on it. The circuit developed to perform the multiplying function is described in Section IV on the Time Amplifier.

v. Gate Circuits:

The Coarse Count Gate circuit must be turned on by the master timing pulse and off by the comparator pulse. It must have a resolution of better than plus or minus .18 microseconds in gating off but may have a greater fixed delay in gating on. In practice coarse count gating could be accomplished by use of a bistable circuit driving a pentode gate tube such as the type 6AS6. The techniques for this type of gate are fully developed.

The fine count gate is much less critical and furthermore is gated with a pulse already of the correct width. A single 6AS6 pentode gate circuit will suffice since the resolution need not be much less than 6 microseconds.

vi. Count Registers:

The Count Registers are ordinary low speed binary counter circuits designed to accept pulses at the rate of 83 kilocycles

per second and having parallel output circuits. They must be arranged to be electrically read-out and reset.

The type of binary registers described above are readily available commercially so further consideration of the count registers is unnecessary.

Upon consideration of each section of the circuit in some detail it becomes apparent that development work was necessary on the Comparator and the Time Amplifier to enable the two circuits to meet the requirements set up for them. When it has been proven that these circuits meet the necessary requirements, the validity of the design will be established.

Sections III and IV deal with the development work done on the Comparator and the Time Amplifier circuits respectively. These sections embody the results of most of the experimental work done.

Section III

The Comparator

3.0 Specifications:

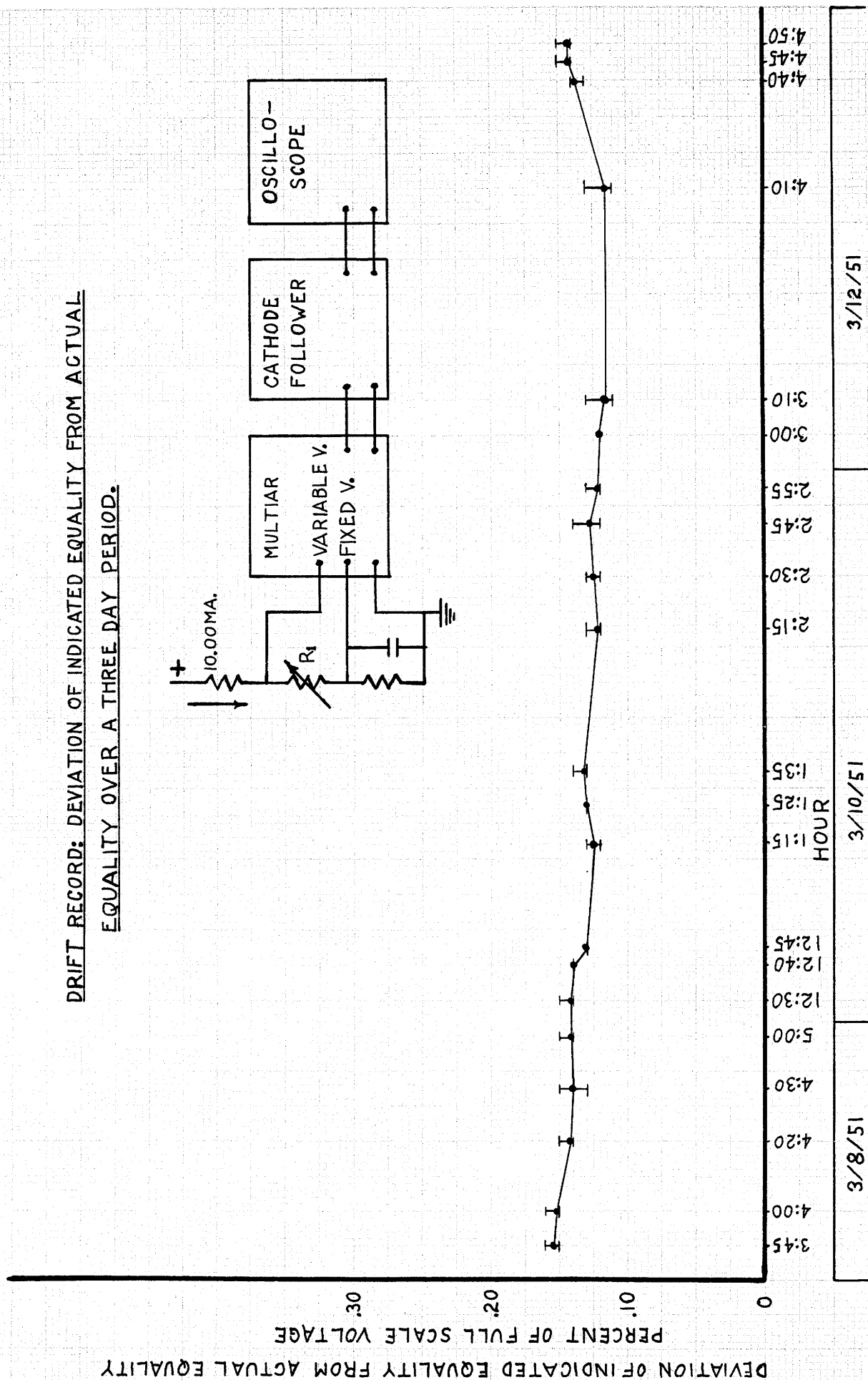
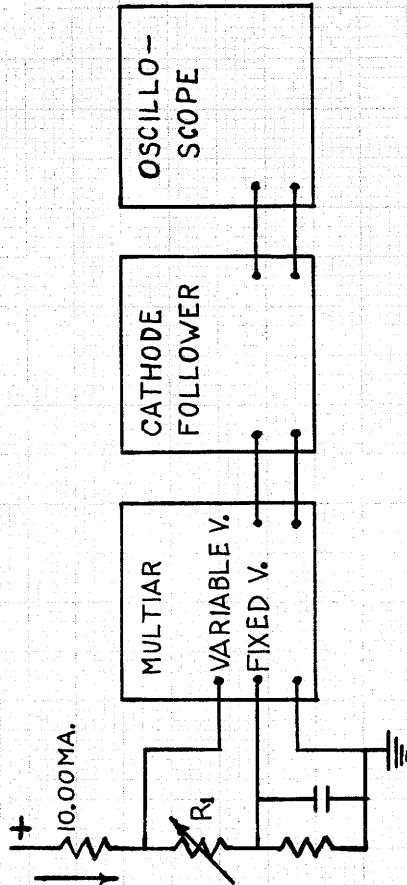
The specifications for the comparator circuit have been given in the previous section. They will be repeated and amplified here for completeness. We consider the function for coding to be a constant during the sampling period. Comparison of this voltage to a sweep voltage having a rate of fall of .267 volts per microsecond is necessary. The voltage traverse of the input must be 102.4 volts and the equality indication must not vary by as much as 0.1 volt in its relationship to the actual equality point over this range. It is permissible to have a constant voltage difference or a constant time delay between the actual equality point and the output pulse, provided the delay is calibrated out. The output pulse is used to trigger two circuits, therefore means must be provided to isolate the comparator from these circuits so that they will not affect its accuracy.

3.1 Experimental Results:

The circuit chosen for development was the Multiar^{4,5} (Fig.2), employing a diode selector and regeneration for high gain in amplifying the break characteristic. The schematic diagram is shown in Fig.3.

That this circuit meets the specifications set up as regards stability and short and long range drift is shown by the graph (Fig.2) on the following page. The measurement made was of the static voltage

DRIFT RECORD: DEVIATION OF INDICATED EQUALITY FROM ACTUAL
EQUALITY OVER A THREE DAY PERIOD.



J.E.G.
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TIME OF EACH SET OF READINGS
Fig. 2

difference between a fixed reference voltage and a variable voltage when the comparator indicated equality of the two. This is plotted as a percentage of full scale voltage. Each point plotted represents a series of from ten to twenty-five successive readings taken at the time indicated on each particular day of the three days on which data was taken. Both the average reading and the maximum excursion to either side is shown since the accuracy depends upon each reading being within the specified bounds, - .05 volts. It can be seen that the bounds are in no case exceeded.

3.2 Circuit Operation:

The action of the Multiar circuit may be explained as follows: The pentode normally is conducting with approximately zero bias and is drawing slight grid current through the grid resistance. The diode is not conducting since the sweep voltage is initially positive with respect to the reference voltage. As the sweep voltage goes negative it approaches the value of the reference and the diode begins to conduct. The conduction of the diode puts the pulse transformer winding 1-2 in the circuit. More important, it causes a slight negative voltage to develop at the grid due to conduction through R_g . Because of the G_m of the tube, this slight negative voltage is amplified at the cathode which feeds the amplified negative voltage back to the grid through the pulse transformer with a 2:1 step-up ratio. This regenerative feedback causes a sharp negative drop to appear at the grid of the pentode, driving it below cutoff. The time constant of the transformer winding causes the cathode voltage to decay slightly at this point and the circuit tends

toward the original condition aided by regeneration. As the grid voltage approaches zero, the sweep voltage takes over to cause the grid to start downward again. This "bouncing" will continue until the sweep voltage has decreased to the point where the tube is cut off. These multiple pulses are not disadvantageous since the comparator output pulse is used to trigger two multivibrators which are insensitive to any but the first trigger. Rise time of the output pulses is 0.5 microseconds.

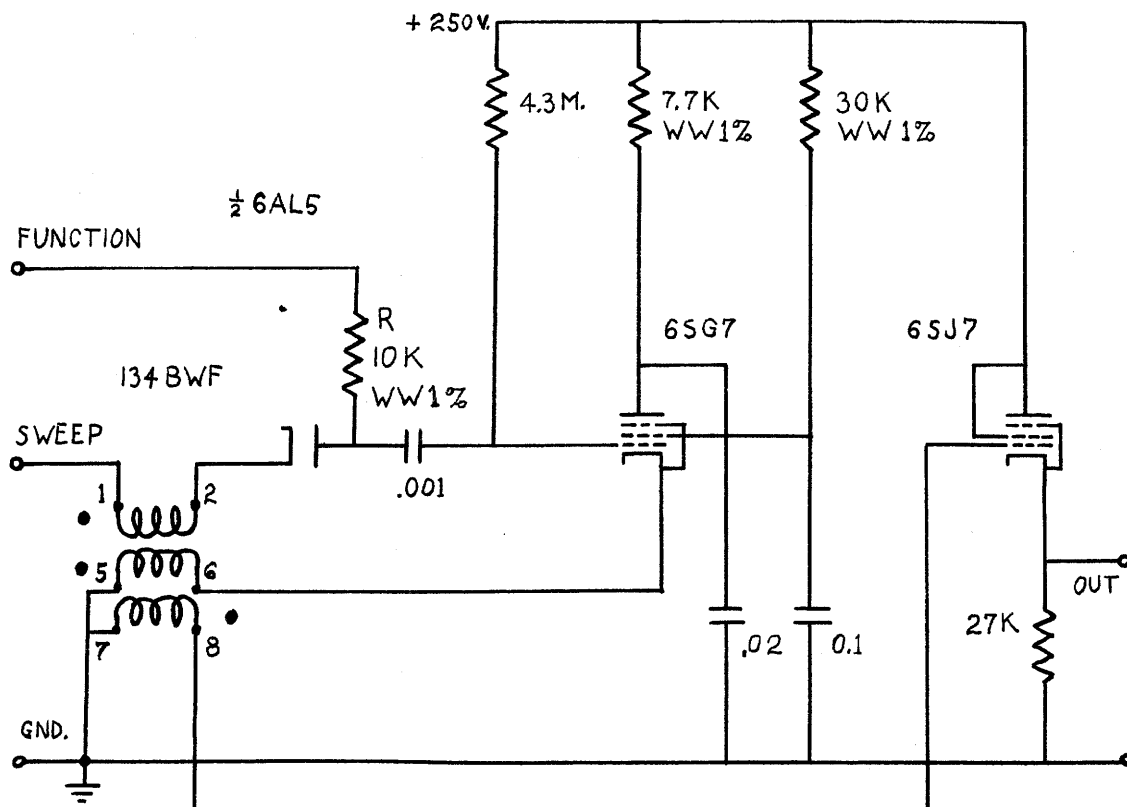


FIG. 3. COMPARATOR

3.3 Circuit Components:

Since precise operation is required of this circuit, the components are necessarily chosen for close tolerances and low drift coefficients. One percent wire wound resistors were used in all cases. Actually the resistors do not need to be very close to their indicated value, it is far more important that they have, low drift, low noise, and low temperature coefficients. The capacitors are not at all critical since they are used in this circuit for coupling or by-passing only. The pulse transformer used was the Westinghouse 134 BWF which has the very good high frequency response required to deliver a fast rising output pulse.

The pentode used in this circuit was the 6 SG7, but other types, namely the 6SH7 and the 6SJ7, were found to work equally well. The requirements on this tube are that it have a high grid to cathode transconductance and small aging effects. Since the tube is operated at zero bias, the transconductance is fairly constant over small changes in tube current.

The most critical element in the circuit is the diode. It operates as the selector, the rest of the circuit is concerned with amplifying its "broken-line" characteristic. The type 6AL5 was chosen for this application because of its low forward resistance, stability, and low interelectrode capacitance. A further discussion of the diode characteristics may be found in the discussion of errors, section 3.5.

It is apparent that other types of circuits may be used to perform voltage comparison. Different types of selectors such as germanium crystals or triodes may be used. Multivibrators or blocking oscillators or ordinary amplifiers may be used to provide gain. Some of these

possibilities as well as further discussion of the reasons for choosing the Multiar for this application may be found in the Appendix, section VI.

3.4 Validity of Method of Measurement:

Before proceeding with analyses of the circuit operation and the experimental results obtained, it might be well to establish the validity of the method of measurement employed.

The circuit used for all the measurements of drift, stability, and circuit dependence on parameter drift is shown in Fig. 2. A voltage divider with a constant current of 10.00 milliamperes flowing through it was provided to supply a fixed and a variable voltage to the Multiar to simulate the function to be coded and the sweep voltage respectively. (The current through this divider was maintained constant by manual adjustment.) Resistor R_1 was varied so that the variable voltage approached the fixed voltage. Apparent equality of the two voltages was indicated by an output pulse from the Multiar which was fed through a cathode follower to an oscilloscope where it was used to trigger a driven sweep. The sweep speed of the oscilloscope was set to be slow enough that a single sweep was visible. Thus a single output pulse could be detected. The output pulse was positive, 18 volts in amplitude, with a rise time of 0.5 microseconds and a duration of 2.0 microseconds.

In lieu of the negative going sweep having a fall rate of about 0.3 volts per microsecond which would be applied in actual operation, the variable voltage mentioned above was provided. This voltage was actually applied in quantized form since R_1 was a decade resistor. It is necessary to show that the results obtained with this variable

voltage applied do not differ significantly from the results which would be obtained if the actual sweep were applied.

With a diode capacity of 3.2 uuf and an assumed stray capacity of about 2.0 uuf, the input time constant is seen to be only .05 micro-seconds. Since the rate of change of the sweep voltage is so low, it might be expected that the dynamic characteristic of the Multiar will not differ greatly from the static characteristic.

Quantized steps of .01 volt were used after it had been established that steps of .001 volt applied did not alter the apparent coincidence point. To further insure that a switching transient was not responsible for the triggering, an R-C filter was inserted in series with the variable voltage supplied to the Multiar. It was found to cause no appreciable change in the coincidence point. It is apparent that once the current through the diode is increased beyond a certain point, the circuit operation is sensibly independent of the applied variable voltage.

The readings for the graph previously presented, (Fig.2) were taken with the diode filament voltage manually regulated to be 6.0 ± 0.1 volt rms for reasons to be discussed subsequently in Section 3.5.

3.5 Analysis and Discussion of Errors:

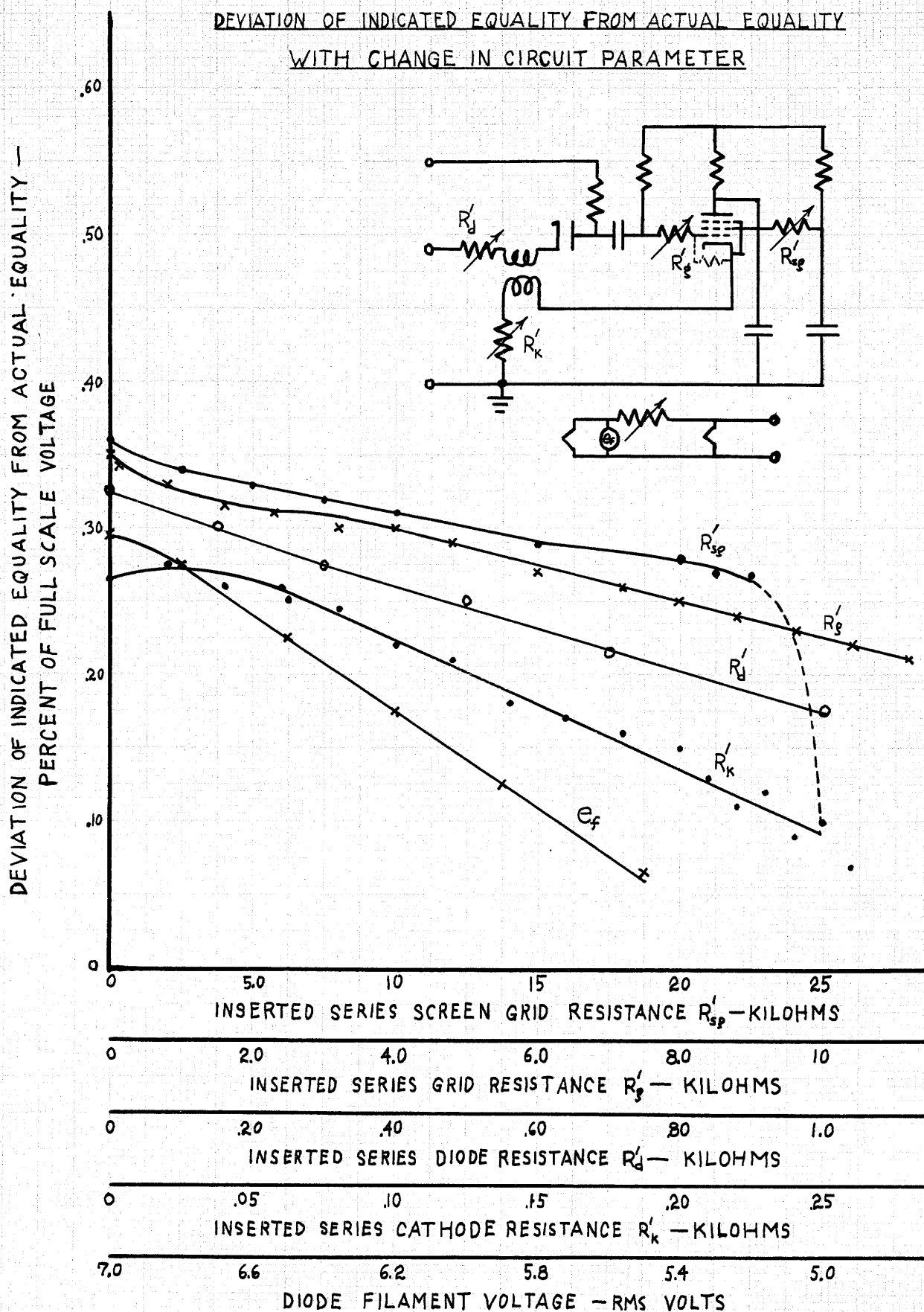
Analysis of the Multiar circuit operation is complicated by the fact that the diode and the grid circuit of the pentode are extremely nonlinear in the region of operation. The diode changes its effective resistance from nearly infinity to 200 ohms along an exponential characteristic.⁴ The grid resistance of the pentode changes its

resistance from a few thousand ohms to practically infinity during the first part of the trigger action. These variable resistances complicate an analysis of the circuit on the basis of feedback amplifiers. On a qualitative basis it is apparent that if the characteristic of the diode is exponential, no combination of its characteristic with linear elements will sharpen the break. It is also apparent that any element which inhibits the feedback path or reduces the gain in this path will cause the required voltage increment across R to be larger to initiate the regenerative action, thus changing the effective coincidence point.

Because of the difficulties mentioned above, the analysis of the circuit operation was carried out on an experimental rather than a theoretical basis. To this end, various parameters in the circuit were varied and their influence on the apparent coincidence point established. In some instances resistances were inserted in the circuit to simulate changes in tube parameters.

For small changes in parameter, the deviation in apparent coincidence point is a linear function of the parameter. For this reason the influence of a change in any parameter on the apparent coincidence point is independent of the setting of the other parameters. Several tests were conducted to insure that this was the case.

The curves for various parameter changes are plotted on a graph (Fig. 4). Since the slope of the curves alone is of importance, the plot is of the percent change in apparent coincidence with the parameter variation. The circuit is redrawn showing the insertion of variable resistances. In each case all but one of the inserted resistors were



set to zero to eliminate interdependence. Note that the resistance scales are not identical since the effectiveness of resistance change depends upon the percentage change rather than absolute change at different parts of the circuit.

Before discussing each individual curve it might be well to point out that another factor not previously mentioned is of importance here. This is the dispersion of successive readings for a given condition. The dispersion indicates the stability of the coincidence indication for any particular set of circuit conditions. The average value of the readings for any point on a curve has no significance unless the range of readings is sufficiently small to insure that extraneous random causes are not affecting the readings. In short, the results must be interpretable through the "noise" of random effects.

In the case of each curve plotted (Fig.4), the points plotted are the average of 5 readings whose dispersion was not more than .01%. As might be expected, changes in some of the parameters causes a change in dispersion of the readings as well as a change in the average reading. This is true of the pentode plate load resistor and of the transformer ratio. For this reason, the plate load resistance was set at effectively zero ohms and the transformer ratio was set at the low ratio of 2:1. The diode load resistor R was set at a fairly low value, 10,000 ohms, for the same reason. For all the other components, the dispersion increase was not significant over most of the range of variation.

The effects of parameter variation may be summarized in a table of coefficients giving the slope of the curve for each parameter. Attention should be paid to the units given for each coefficient since

the relative importance of each parameter's variation depends upon both the coefficient and the probable variation of the parameter.

Parameter Varied	Effect
Filament voltage	.17 <u>percent</u> fil. volt-rms.
Pentode load resistance	(negligible)
Plate supply voltage	(negligible)
Screen Resistance (inserted)	-.01 <u>percent</u> kilohm
Control grid series resistance (inserted)	-.05 <u>percent</u> kilohm
Diode series resistance (inserted)	-.17 <u>percent</u> kilohm
Cathode series resistance (inserted)	-.90 <u>percent</u> kilohm

The effect of filament voltage variation has proven to be of greatest importance. While the coefficient does not appear to be very large, fluctuations of a few tenths of a volt in filament voltage are not uncommon in general practice. As a matter of fact, it is difficult to regulate the filament supply voltage manually to within a tenth of a volt with the aid of an ordinary a-c meter covering the necessary voltage range. This means that about .02% random variation may be expected on the drift record (Fig.2). Aging effects may be considered together with filament voltage drifts because the effect is the same, the cathode temperature changes.

Because of its great importance, it might be well to consider the mechanism of drift due to filament temperature change in a diode. (The filament temperature effects in the pentode are negligible in the region of normal operation of the tube.) The sketch shown in Fig.5 is the low current characteristic of a typical 6AL5 diode plotted on a semi-logarithmic scale. The fact that the curve is approximately linear shows that the current is an exponential function of the voltage across the tube. We may consider that the multiar circuit triggers with a certain voltage across the diode load resistor, R , each time. In other words, the diode current for triggering is constant. Therefore, a filament temperature change is equivalent to shifting the curve to the left or right along the voltage scale. The voltage applied to the diode circuit to effect triggering is therefore a function of cathode temperature.

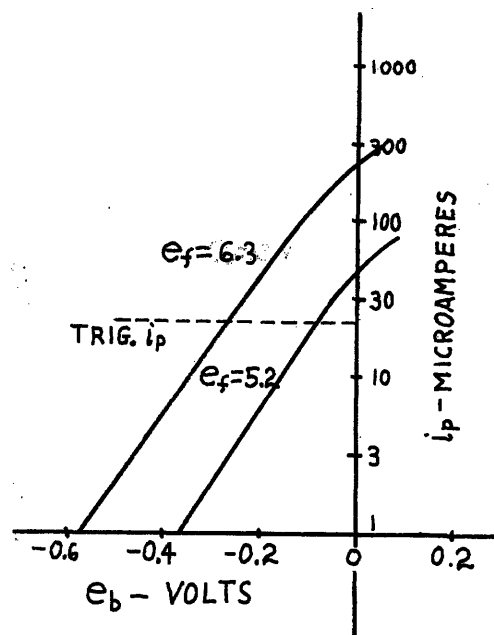


FIG. 5. DIODE CHARACTERISTIC

It is apparent that some sort of regulation must be applied to the filament current of the diode for accurate operation of the circuit. Use of a regulator such as a carbon pile with direct current or a saturable reactor with alternating current will be necessary in this circuit. As an alternative or perhaps as a further aid, the circuit of Fig. 6a may be employed to partially balance out the effect of the original diode.

Compensation is provided by the two diodes generating equal voltages dependent upon the filament temperature with opposite polarity. The diodes should be in the same envelope and be matched for best results. An equivalent circuit is shown in Fig. 6b. It may be pointed out however, that addition of capacitance across resistor R is undesirable since it adds a transient effect when the sweep voltage is used. Another important point is that noise generated in the compensating diode may trigger the circuit near the coincidence point. Measurements made with this circuit were inconclusive. The dispersion of readings at each point was much higher than could be tolerated, but the curve itself showed anomalies. Lack of time prevented further investigation. It is possible that the method of measurement was at fault. This circuit merits further investigation.

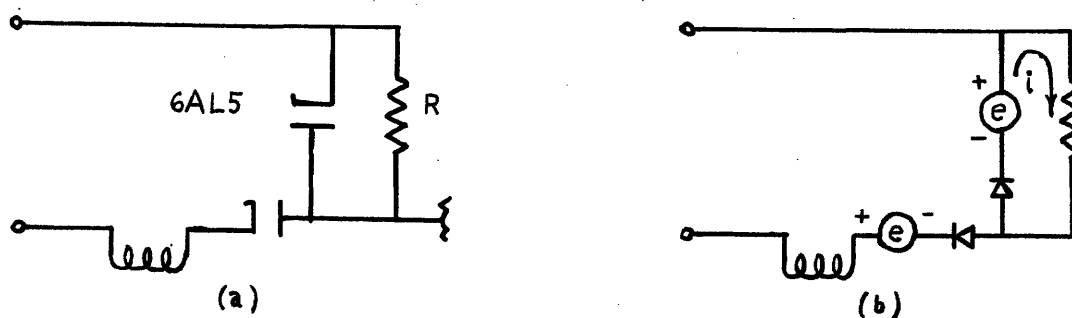


FIG. 6. DIODE COMPENSATION

The coefficient associated with the variation of an inserted series screen resistor is of little importance in itself but it does have an important implication; the transconductance of the amplifier tube may be varied over wide limits with little effect on the trigger point.

Below a certain point, however, the effective coincidence voltage changes radically and the triggering is spasmodic. In short, a certain minimum grid to cathode transconductance is necessary for normal operation but an increase over this minimum benefits circuit operation little. This is highly desirable since it means that aging effects in the pentode may be virtually ignored. This is due to the fact that regeneration is used, making the rise of the output pulse dependent only on the physical circuit time constants.

The other three resistors varied are all in the regenerative loop and their influence on circuit operation may be expected to be greater. The effect of adding a series control grid resistance, though greater, is also of minor importance. From the circuit of Fig.4 it can be seen that the effect is to add a voltage divider circuit consisting of the inserted resistor and the conducting grid resistance shown dotted. The effective grid characteristic is changed only in the positive grid region of the output pulse and so the change is of little importance. No simple way of changing the grid characteristic of the tube was found. To simulate the shifting of the grid current-voltage curve along the voltage axis, a voltage was added in series with the grid but variation from -2 to +2 volts produced no change whatsoever. The fact that the grid is supplied through a large series resistor to the plate supply provided automatic adjustment of the grid bias to the correct value.

Inserting resistance in series with the diode may be considered to be the same as increasing the resistance of the diode at the point where effective coincidence occurs. A certain current must flow through the resistor R to initiate the triggering action. With a resistor

in series with the diode a higher voltage is required to supply this current.

Another way of looking at this condition is illustrated in Fig.7, below. The equivalent feedback circuit is shown with the diode replaced by a variable resistor, r_d . Effectively, the diode starts out at infinite resistance and reduces its resistance until the gain around the closed loop is 1 at which time regeneration causes the diode resistance to drop drastically. The gain around the loop is the product of the gain from the cathode to the grid and the gain from the grid through the tube to the cathode. Assuming the transformer to be ideal, the cathode to grid gain is simply

$$\frac{e_g}{e_k} = \frac{2R}{R + r_d' + r_d} - 1$$

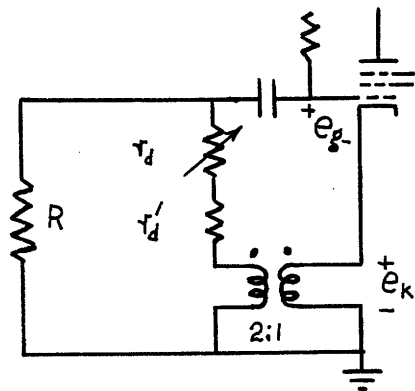


FIG. 7. EQUIVALENT CIRCUIT

where r_d' is the inserted resistance and r_d is the dynamic resistance of the diode. When r_d' is increased, r_d must be decreased to make the loop gain equal to one. To accomplish this, triggering must occur on a different part of the diode characteristic where the dynamic resistance is smaller.

This part of the investigation illustrates the effect of a change in the shape of the volt-ampere characteristic of the diode. It is felt that such changes will be small enough to be virtually ignored because the shape of the diode characteristic in the low current region

is essentially an exponential dependent upon the distribution of velocities in a cloud of thermally excited electrons and the tube geometry neither of which change with age.

Reference to Fig.7 makes clear the reason for the large effect of increases in the cathode resistance. The unbypassed cathode resistor simply causes degeneration, reducing the gain from the grid to the transformer terminals in the cathode circuit. As a consequence, the diode must be at a lower resistance point on its characteristic when triggering occurs. Ordinarily the only resistance in the cathode is that of the transformer primary which in the case of the Westinghouse 134 BWF is about 10 ohms. This resistance does not change appreciably even over long periods of time, and does not change significantly with temperature.

3.6 Summary and Conclusions:

The preceding exposition establishes the Multiar circuit as suitable for operation in a circuit with a resolution of one part in a thousand. Figure 4, which shows drift over a period of three days represents the results of optimization of the circuit parameters. The drift was within the required bounds for operation with 0.1% accuracy.

The chief cause of inaccuracy has been shown to be filament temperature drift in the diode. It is possible to conclude that other causes of drift are relatively insignificant over short periods of time and may be calibrated out over long periods of time. This is provided, of course, that suitable precaution is taken in construction to insure that components have low noise and low thermal coefficients and are

stable over long periods of time.

Both compensation and filament voltage regulation will be necessary for dependable operation of the Multiar. The fact that the circuit uses regeneration makes it unnecessary to provide gain regulation and makes the circuit relatively insensitive to the characteristics of the pentode. In other comparator circuits where regeneration is not used, changes in characteristics of tubes other than the diode will cause instability and drift.

Section IV

The Time Amplifier

4.0 Specifications:

Reference to section II, The Proposed System, indicates that basically the Time Amplifier is required to recognize and measure a time interval of from 0 to 12 microseconds and to deliver a pulse which has a length 32 times the input time interval minus 12 microseconds. When the input pulse is .375 microseconds, the output pulse is of zero width. For smaller input time intervals the output pulse must be zero also. The equation governing the action of the time amplifier is:

$$T_o = 32T_i - 12 \text{ microseconds.}$$

4.1 Experimental Results:

Figure 8 is a plot of the experimental results obtained in testing the time amplifier circuit designed for application to this quantizer. The duration of the output gate pulse is plotted as a function of the input time interval. The points are actual readings, but the line drawn through them is the theoretical equation given above. It is not useful in this case to obtain the best line through the points because the readings have significance only with respect to the theoretical curve. The deviations of the readings from the theoretical curve are also plotted together with the allowable limits of error.

Since the output pulse is used to gate pulses with a separation of

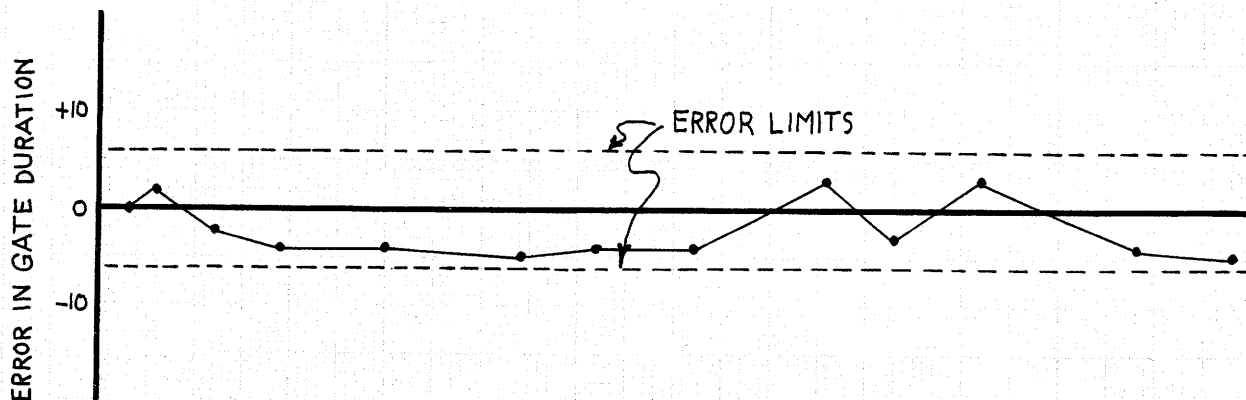
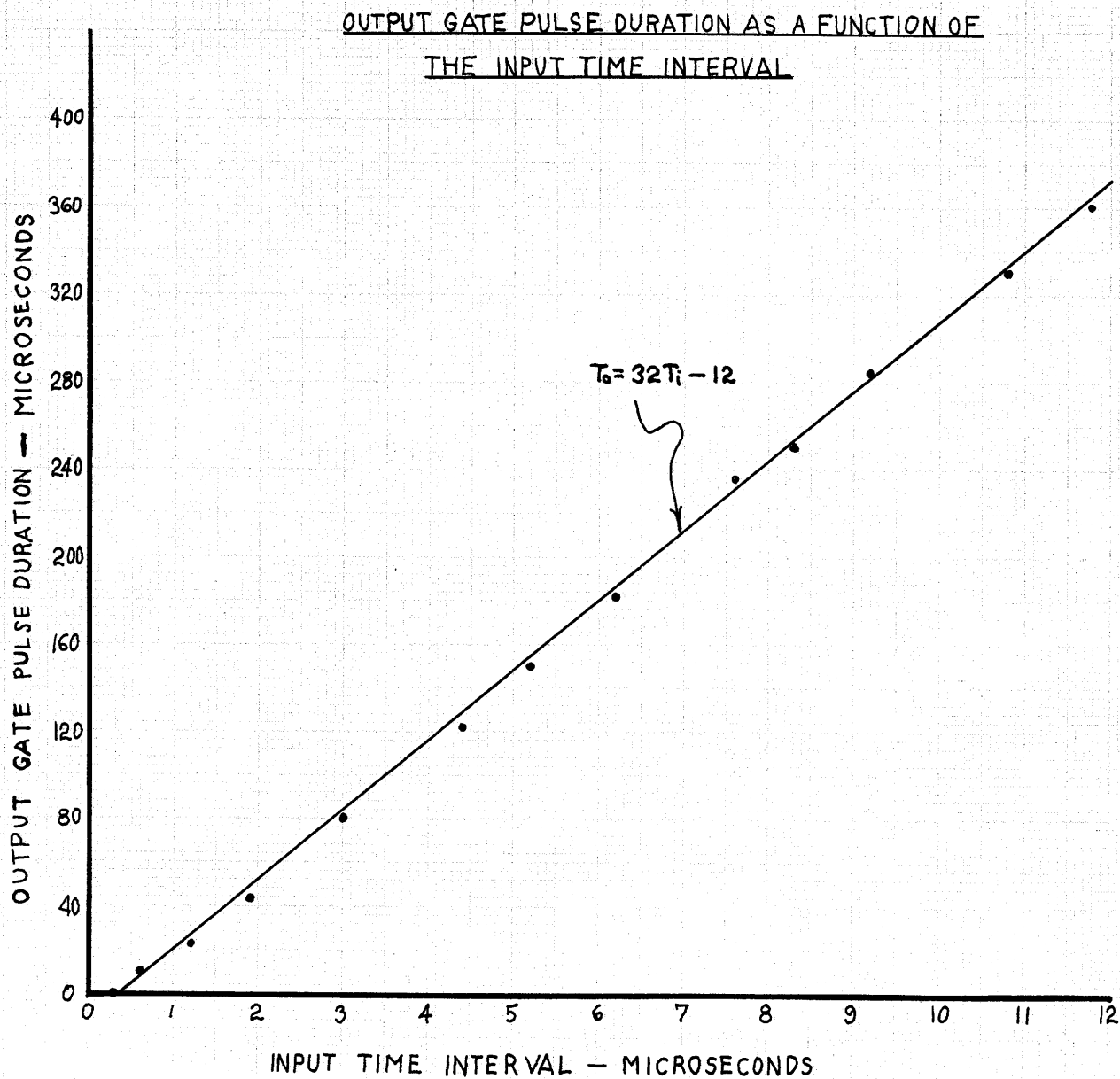


Fig. 8.

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12 microseconds, the allowable limits of error are plus and minus 6 microseconds. A certain experimental uncertainty arises from difficulty in measuring the input time interval. It was estimated that the uncertainty in this measurement was .1 microsecond at a minimum so the uncertainty in the output pulse was at least 3.2 microseconds. The average error was -2 microseconds showing that perhaps the calibration of the circuit was not exactly correct.

The additional functions of the time amplifier circuit are more or less incidental to the multiplication process. The readout and reset signal is simply the trailing edge of a monostable multivibrator pulse which is used to switch a sweep circuit on. The so-called crossover problem must be handled somewhat more extensively. The effect in question is the possibility of a 12 microsecond pulse being counted by both the coarse count circuit and by the fine count interval measurement circuit, due to its finite width. The problem will become more clear when the precise mechanism of measurement is discussed later in this section. At that time the proposed treatment of the problem will be fully explained.

The input time interval is marked by two pulses. The beginning is signified by the comparator pulse and the end, by the next coarse count pulse. Each of these pulses has a finite width and a certain rise time. To effectively delineate the interval of time, the Time Amplifier must be triggered by the same point on each pulse each sampling period. A constant time lag may be calibrated out but jitter in the difference between pulse times must be limited to less than the interval corresponding to a fine count, namely .375 microseconds. It must be

remembered that this jitter appears in the output pulse multiplied by 32.

4.2 The Block Diagram:

The block diagram (Fig. 9) must be referred to at this point to facilitate explanation of the operating principles of the Time Amplifier. Only that portion of the block diagram blocked off by the dotted line was constructed and tested. This section contains the input interval measurement, the multiplication and subtraction, and the gate pulse generating circuits. It will be possible to discuss the operation of this section in more detail in the presentation of the schematic diagram. At that point the significant waveforms produced in this part of the circuit will be reproduced to aid discussion. For the present the action of the overall Time Amplifier circuit will be discussed.

To initiate the action of the Time Amplifier the comparator pulse triggers the Sweep Start Multivibrator, which is monostable. It supplies a negative pulse with duration slightly longer than the maximum possible fine count gate width to the Fine Sweep circuit causing the sweep to start. The comparator pulse also goes through a delay of δ , equal to the width of the coarse count pulses, to trigger another monostable multivibrator, the $(12 - \delta)$ Gate Generator. The δ Delay is supplied by any simple fixed delay circuit and is necessary to the operation of the Crossover Coincidence circuit but not of importance to the basic operation of the Time Amplifier. The $(12 - \delta)$ Gate Generator generates a fixed gate of width $(12 - \delta)$ microseconds which is applied to the Single Pulse Gate which in turn gates one of the count pulses through it to trigger the Sweep Stop Multivibrator. The Sweep Stop Multivibrator

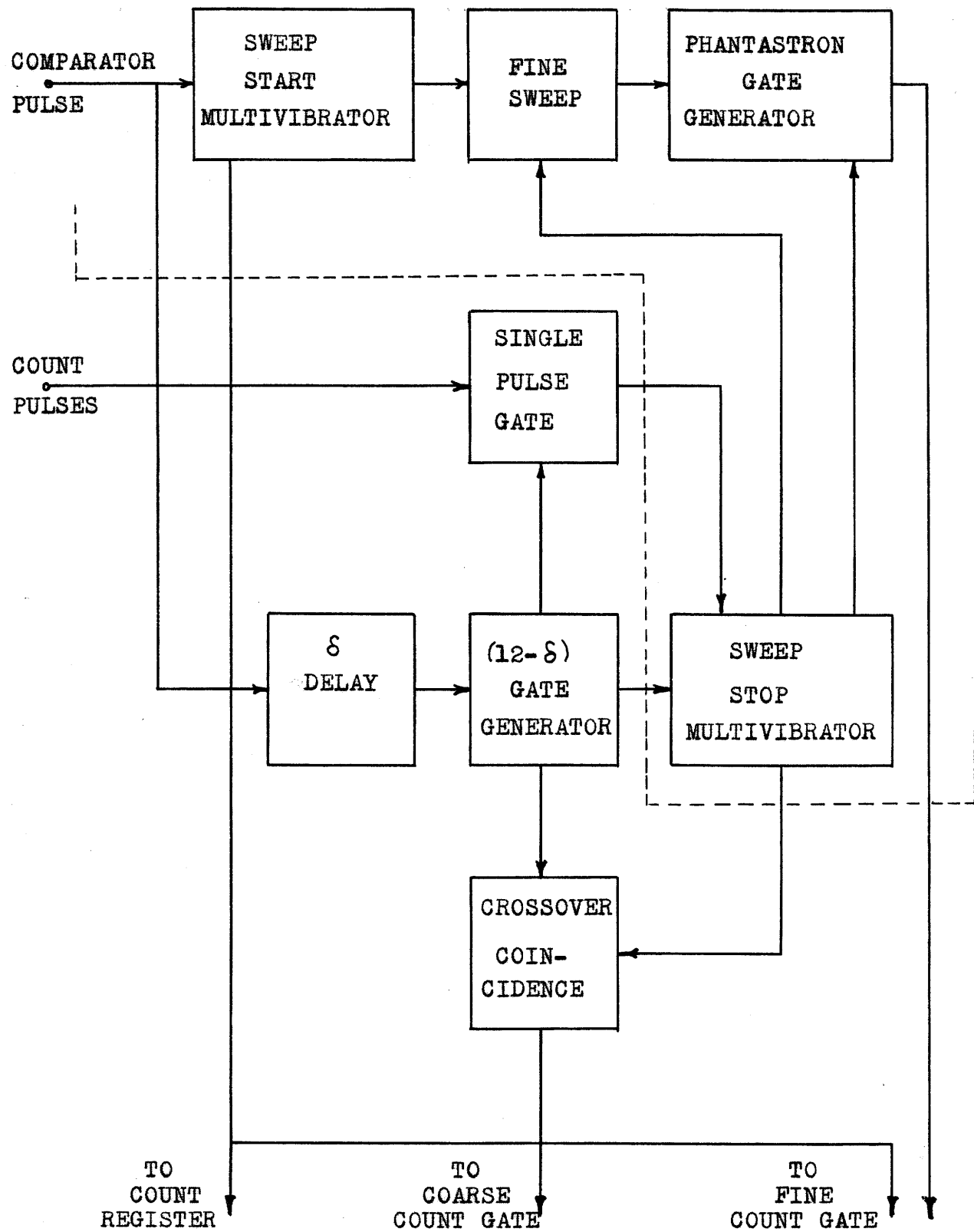


Fig. 9. TIME AMPLIFIER BLOCK DIAGRAM

supplies a positive pulse of approximately the same duration as the sweep start pulse to the Fine Sweep circuit to stop the fine sweep and to hold the sweep voltage at the value it has attained. This voltage is directly proportional to the input time interval.

The leading edge of the Sweep Stop Multivibrator pulse is differentiated and applied as a trigger to the Phantastron Gate Generator to trigger it on. Meanwhile, the attained value of the Fine Sweep voltage is applied to the Phantastron Gate Generator to set the starting point of the phantastron sweep. The starting voltage of a phantastron sweep generator determines the total time of sweep, since the rate of sweep and the ending point of the sweep are fixed. The duration of the sweep is the same as the duration of the screen voltage pulse which is used as the fine count gate. It appears, then, that the Phantastron Gate Generator produces a pulse width proportional to the value of voltage fed in from the Fine Sweep. Subtraction of the 12 microseconds is also performed in this part of the circuit but the mechanism of this will be discussed later.

If the comparator pulse were by chance exactly coincident with a coarse count pulse, the beginning of that coarse count pulse might be fed into the coarse count register. If then the delay of one pulse width were not provided before opening the Single Pulse Gate, the trailing end of that same pulse might pass through and trigger the Sweep Stop Multivibrator. This would result in a zero fine count when a maximum fine count is desired since the Fine Sweep would be immediately turned off when it should have been allowed to run until the next

count pulse appeared. Introduction of the δ Delay introduces a new problem, however. If the comparator pulse occurs just before a coarse count pulse, the coarse count pulse would occur entirely within the delay time and would not appear in either the coarse count register or in the Single Pulse Gate. As a result, the Sweep Stop Multivibrator would not be triggered at all. To eliminate this trouble, the trailing edge of the $(12 - \delta)$ gate pulse is arranged to trigger the Sweep Stop Multivibrator if it is not already on. Triggering the Sweep Stop Multivibrator at this time means that the last coarse count pulse should have been counted in the coarse count register. To supply this coarse count the Crossover Coincidence is arranged to feed a single pulse through the Coarse Count Gate circuit whenever the Sweep Stop Multivibrator has been triggered by the trailing edge of the $(12 - \delta)$ gate.

A more detailed consideration of the crossover problem together with the proposed circuit design to eliminate the difficulty may be found in the Appendix, Section VI of this report.

4.3 Theory of the Multiplier:

Before plunging into the details of the physical circuit it will be well to investigate the theory of the computation accomplished in the circuit. It has already been described how the Sweep Start and the Sweep Stop Multivibrators allow the Fine Sweep to attain a certain voltage which is held, and how the Phantastron produces a sweep which starts at this voltage and ends when it reaches another constant voltage. The sketches shown in Fig. 10 and the following algebraic derivation

show how the computation is accomplished using the characteristics of the circuits.

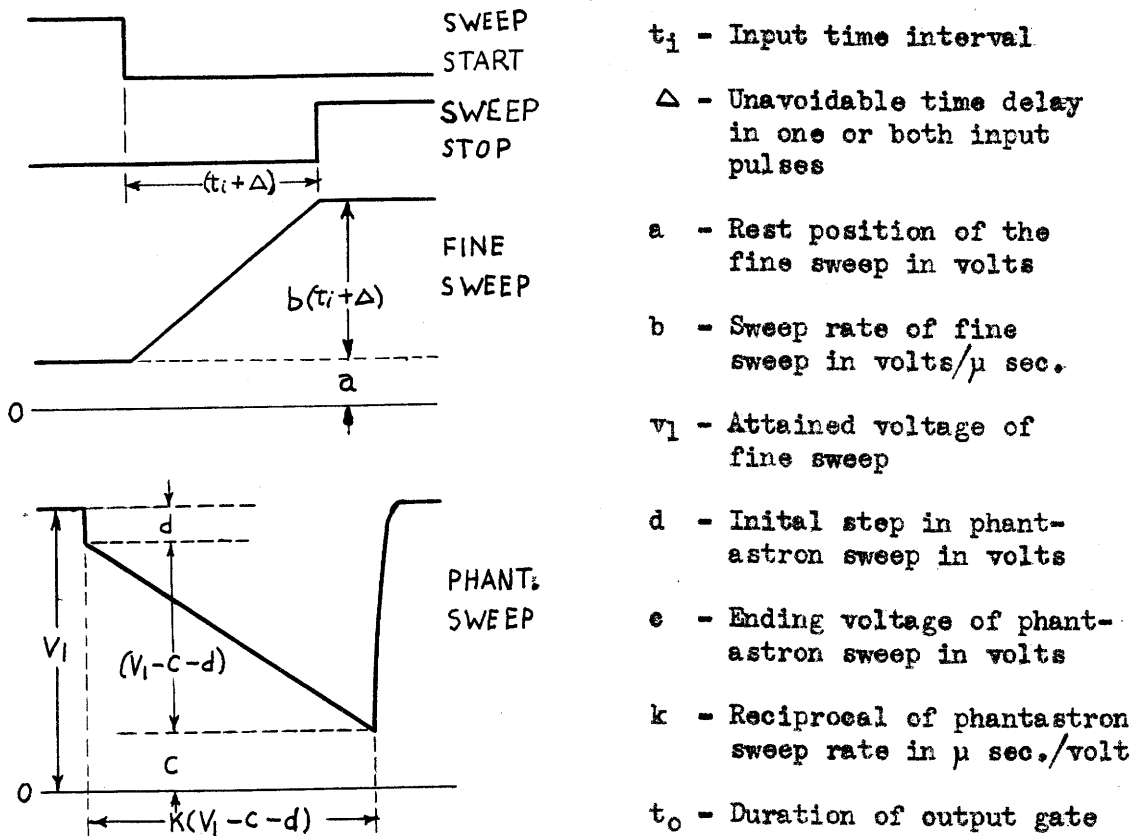


FIG. 10. TIME MULTIPLICATION

$$V_1 = b(t_i + \Delta) + a \text{ volts}$$

$$t_o = k(v_1 - c - d) \mu \text{ sec.}$$

$$t_o = k(bt_i + b\Delta + a - c - d) \mu \text{ sec.}$$

$$t_o = kbt_i + k(b\Delta + a - c - d) \mu \text{ sec.}$$

Set:

$$kb = 32$$

$$k(b\Delta + a - c - d) = -12 \mu \text{ sec.}$$

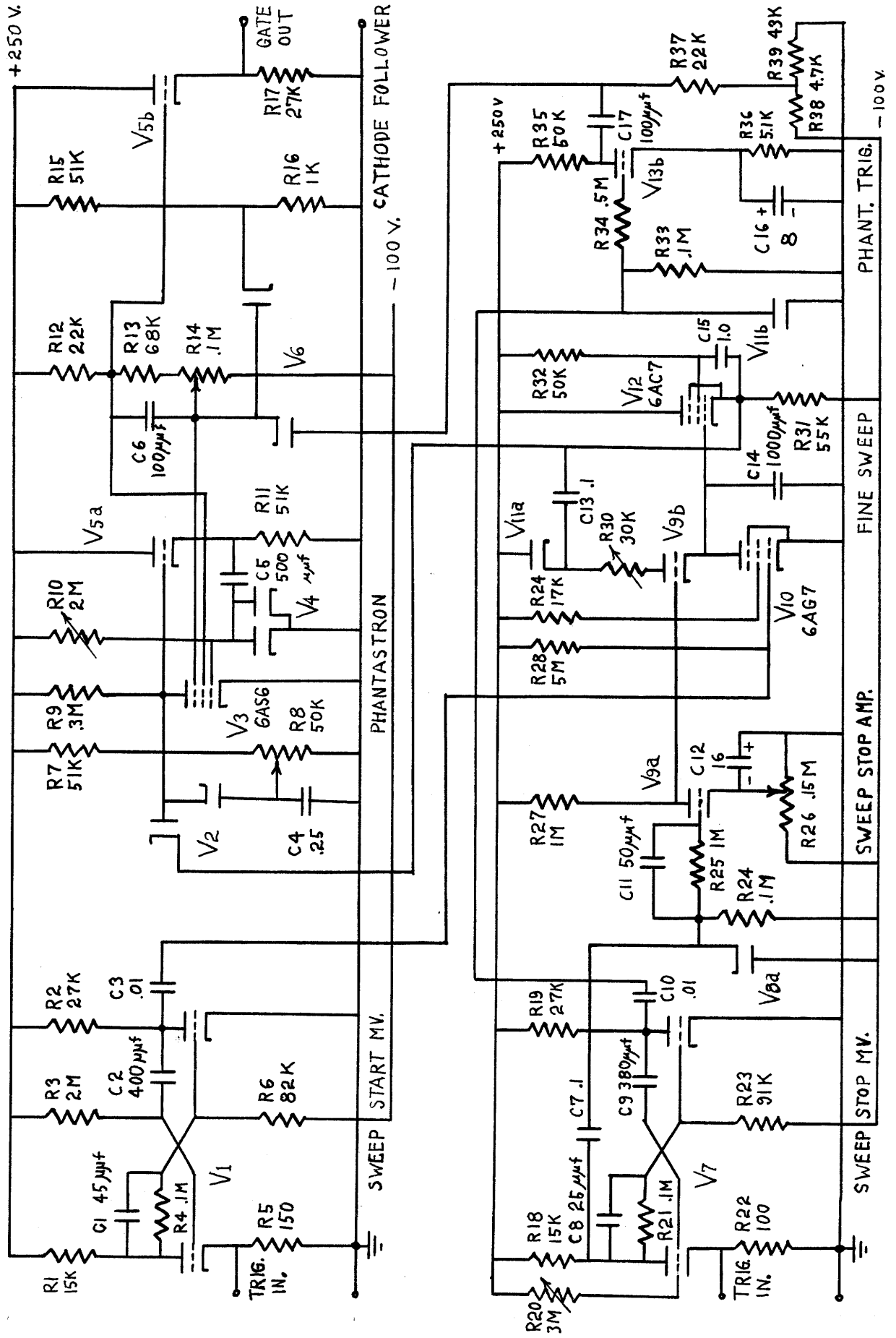
$$t_o = 32t_i - 12 \mu \text{ sec.}$$

The constants a and (d) are fixed by the circuit parameters used and in practice (a) will be set at a fixed value also, though it is theoretically variable. The sweep rates (b) and $(1/k)$ as well as the Phantastron sweep ending voltage, (c) , are continuously variable and may be set to satisfy the two conditions specified. It will be convenient to simplify the settings even further by arbitrarily setting (b) at a convenient value and providing for calibration by variation of the phantastron sweep rate $(\frac{1}{k})$ and ending voltage (c) .

4.4 The Schematic Diagram:

The schematic diagram of what may be termed the "computing" elements of the Time Amplifier circuit is shown in Fig. 11. Figure 12 is a chart of the waveforms produced in the circuit. The drawings are reproduced from tracings of the actual oscilloscope pattern made with the aid of an Oscillotracer. Both the entire waveform and an expanded view of the leading edge of each waveform is shown. The actual period of the waveforms is 996 microseconds but only the portion shown here is of interest since the remainder of the period is recovery time. The waveforms will in general be different each sampling cycle since the fine count will fluctuate rapidly with slight changes in the input function. The waveforms shown here are for an input interval of approximately 10 microseconds corresponding to an output pulse width of approximately 308 microseconds.

For the time being we shall assume the proper triggers fed into the Sweep Start and Sweep Stop circuit. The circuits used to generate these pulses are discussed in the Appendix. As may be seen from the



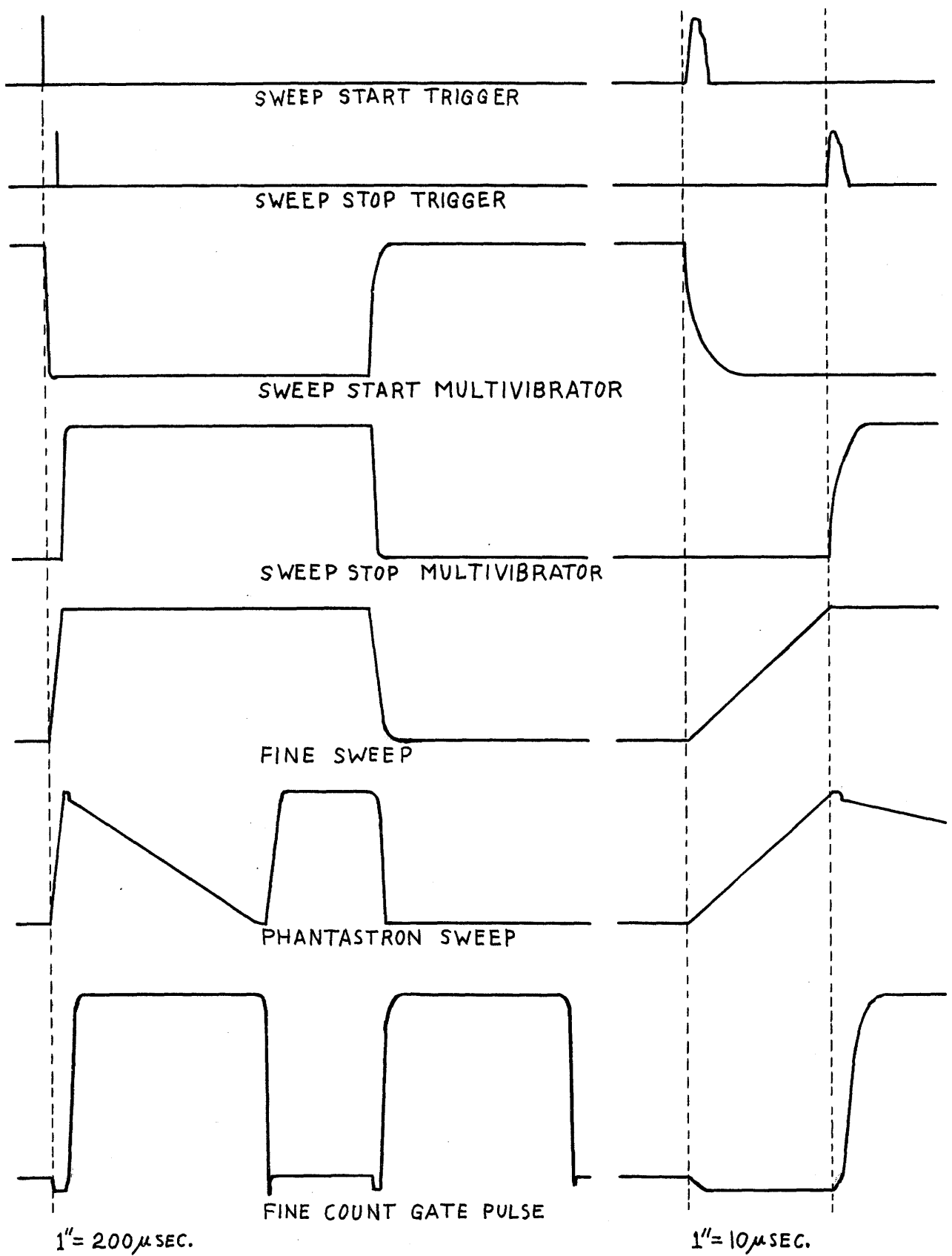


FIG. 12. TIME AMPLIFIER WAVEFORMS

the chart of waveforms (Fig.12) the input triggers are of about 1.5 microsecond duration.

The trigger to the sweep start multivibrator, V1, is fed in on the cathode of the normally conducting tube, flipping the monostable multivibrator to the abnormal state. Its timing circuit keeps it in that state for approximately 400 microseconds at which time it flips back to its normal state. The waveform taken from the plate of the normally off tube is a negative rectangle of 400 microseconds duration which is used to cut off V10, normally at zero bias. The expanded view of the sweep start trigger and sweep start multivibrator waveforms shows that the multivibrator is triggered by the leading edge of the trigger with negligible delay. It should be noted that although the multivibrator waveform is not perfectly square, only the first 10% of the drop is actually used to cut off V10. A similar situation exists for the sweep stop waveform.

Tubes V9b, V10, V11a, and V12 comprise the Fine Sweep Generator. The circuit is basically that of a bootstrap linear sweep generator* with the exception that V9b is inserted in the sweep rate determining network composed of R30 and C14. Since V9a is cut off in the normal condition, the grid of V9b is tied to the plate supply through R27 and V9b is drawing slight grid current to maintain itself at a slight positive bias. The chain V10, V9b, and V11a is conducting, holding the voltage on C14 down to a low value, approximately 25 volts. When V10 is cut off by the sweep start pulse, the circuit acts like an ordinary linear sweep generator. Tube V9b acts as though it were a

* See Sec. 7 and 8 of Ref.4 for a discussion of bootstrap sweep generators.

resistor with a value equal to its static resistance. For the 6SN7 operated at slight positive bias, the static resistance is practically equal to the dynamic resistance. This means that as the grid to cathode voltage changes slightly during the sweep, there will be practically no effect on the linearity of the sweep. This is important because as the cathode voltage of V9b rises with the sweep, the voltage across R27 changes, changing the grid current drawn from V9b. A change in grid current produces a change in grid to cathode voltage which in turn changes the effective static plate resistance of the tube. Briefly, then, V9b acts as a "grid follower" and essentially remains a constant resistance so that the Fine Sweep Generator generates a linear sweep when triggered on by the Sweep Start Multivibrator.

The triggering action of the Sweep Stop Multivibrator is identical to that of the Sweep Start Multivibrator. In this case, however, the positive going waveform is used. It is used to turn on V9a which is normally just below cutoff. The waveform at the grid of V9a is clamped positive with respect to -100 volts so that only the first 20% of the rise of the multivibrator waveform is used to bring the tube into the positive region. When V9a conducts, its plate is immediately driven negative to some value below ground. This will cut off V9b no matter what part of the fine sweep it is on because the cathode of V9b is held to the attained sweep voltage by C14. With V9b cut off C14 has no discharge path and so holds its charge until either V10 or V9b again conducts. Neither of these tubes will conduct for about 400 microseconds until both the sweep start and sweep stop voltage pulses are ended,

at which time the entire Fine Sweep Generator returns to normal. The fine sweep waveform illustrates the precise operation of the circuit which is linear to within 1.0%. The jitter in turning the Fine Sweep Generator off and on is so small it was not discernable on a 0.5 microsecond per centimeter oscilloscope display.

The waveform of the Fine Sweep Generator is fed to the Phantastron plate through a diode for isolation. The Phantastron is a conventional screen coupled phantastron circuit and needs little comment.* When it is triggered on it generates a linear sweep starting at whatever voltage the plate happens to be set at, with a sweep rate set by the values of R10 and C5. The sweep ends when the plate voltage becomes so low that diode V2b conducts, holding the plate voltage at the voltage set on R8. This adjustment is that described in Section 4.3 as voltage (c) and determines the constant time subtracted during multiplication, in this case 12 microseconds.

The Phantastron is triggered in the following manner: A negative going rectangle from the Sweep Stop Multivibrator is amplified and inverted in V13, differentiated by C17 and R37, and applied to the suppressor of the Phantastron through a diode, V6a. Since this trigger occurs a fraction of a microsecond after the sweep is stopped and since the sweep is stopped by a coarse count pulse triggering the Sweep Stop Multivibrator, the Phantastron sweep is started just after a coarse count pulse. The importance of this will become apparent subsequently.

As has been previously pointed out, the screen voltage of a Phantastron sweep circuit exhibits a positive pulse for the duration of the sweep. This pulse is used as the fine count gate shown in the last

* See page 197 of Ref. 4.

waveform of Fig.12. This waveform shows that a spurious pulse is also generated. This spurious pulse is caused by the Phantastron being triggered by the negative drop of the fine sweep waveform applied to its plate. This is not serious, however, because the waveform of the Sweep Stop Multivibrator may be used together with the fine count gate pulse generated by the Phantastron circuit in a double coincidence circuit to actually gate the fine count.

The small negative step of the Phantastron screen voltage is due to the linear rise applied to the plate of the Phantastron being applied to the control grid through the cathode follower V5a and capacitor C5. The diode V4 has been provided to limit the positive step on the control grid, thereby limiting the negative step on the screen.

It was pointed out above that the Phantastron sweep is started just after a coarse count pulse. This means that the fine count gate starts just after a coarse count pulse. For this reason the same train of pulses 12 microseconds apart may be used for the fine count as for the coarse count.

4.5 Measurements on the Time Amplifier:

Measurement of the characteristics of the Time Amplifier circuit were carried out by making measurements of the input time interval between pulses and the output pulse width using an oscilloscope trace with externally generated time markers superimposed upon it. The time markers were obtained from oscillators previously calibrated against a crystal oscillator. Readings of the input time interval were made

using 1.0 microsecond markers except that those intervals in the range of from 0 to 3 microseconds were measured using 0.2 microsecond markers. Measurement of the output pulse was made with the use of 5 microsecond markers.

It was not possible to measure the input time interval to an accuracy of greater than 0.1 microsecond with the equipment available. This is an accuracy of one part in 120 or about 1.0%. The output pulse time was even more difficult to measure directly in this manner because of the small marker spacing compared to the pulse width. Due to difficulties connected with the finite rise time and fall time of the output pulse and the limit on sweep speed necessary to view the entire waveform, measurements of the output pulse width could be made to about half a marker interval or about 3 microseconds. Since the output pulse had a maximum time of 372 microseconds, it could be measured to an accuracy of about 1.0%. The overall accuracy of measurement was of the order of 2%.

The circuit used to generate the trigger pulses used for the test is of minor importance so long as it can be demonstrated that the pulses meet the requirements as regards rise time and jitter. Measurements of the input time interval established that they did meet requirements. For the sake of completeness, however, the circuit actually used is described in the Appendix.

4.6 Summary Discussion of the Time Amplifier:

Although only the "computational" elements of the Time Amplifier were constructed and tested, it is felt that the validity of this method

has been proven since the remaining circuits may be of conventional design. Suggested designs for the remaining circuits of the Time Amplifier are given in the Appendix where the so-called crossover problem is discussed.

The accuracy that this circuit is required to maintain is one count in 32 or about 3%. The method of measurement admitted of an accuracy no greater than about 2%. In all probability, then, the errors plotted in Fig. 8 are pessimistic. Measurements were taken over a period of a week and no evidence of instability either over short or long periods of time was found. (By instability is meant drift outside the limits of error.)

Short of building the entire quantizer, there is little likelihood of measuring the action of the Time Amplifier except with an effectively constant input. The circuit recovers completely during each cycle, however, making each cycle of operation independent of previous cycles.

Section V

Conclusions

5.0 Summary:

The constraints imposed upon the design of a quantizer, that it have a sampling rate of one thousand times per second and that it have a resolution of one part in a thousand seem to limit the choice of method to purely electronic means. While it is easy to obtain circuits operating at high repetition rates, difficulty is encountered in designing equipment to work with voltage resolutions of the order of 0.1%. These considerations have guided the design of the quantizer presented here. The design evolved minimizes the circuits working at high accuracy in the voltage domain to two, the Main Sweep Generator and the Comparator. Several circuits are required to operate to a high resolution in the time domain, but this presents much less of a problem.

A great deal of development work and research has been devoted to the development of extremely accurate sweep generators but little has heretofore been done on voltage comparators of comparable accuracy. In the proposed design for a quantizer it was found necessary to definitely establish whether the resolution and stability necessary could be obtained with the type of circuit proposed.

In this thesis the one questionable high resolution component has been exhaustively investigated and proven out. We may now assume that the goal of a high resolution is attainable in this type of quantizer.

The real heart of the method employed in the projected device is

the time amplifier. No conventional means for supplying the time multiplication necessary to the method chosen was found, hence it was necessary to design and test a suitable circuit. This particular circuit was designed with due regard to the accuracy necessary from it. As a result, the circuit produced had all the necessary qualifications required for the proposed method of quantization. We may regard this as conclusive evidence that the proposed system is a valid method of quantization which can meet the original specifications.

5.1 Suggestions for Further Study:

It might be pointed out that while it is possible to obtain the necessary main sweep circuit from already published works, the rigorous requirements dictate the use of a complicated and delicately adjusted circuit. In particular, difficulty will be encountered in meeting the extremely precise triggering time and starting voltage stability requirements. A means whereby many of the stringent requirements on the sweep generator may be removed might be provided through the use of two comparator circuits, one to set the effective start of the sweep by an indication of the exact instant it passes some fixed voltage near the starting voltage, and the other used as described previously. In this way the effort expended in the development of the Multiar comparator could be used to remove some of the stringent requirements on the sweep generator.

There are several problems connected with this scheme which should be investigated. One is the fact that the train of coarse and fine

count pulses must be initiated exactly coincident with the indication from the first Multiar circuit. The other is the possibility that the disturbance caused by the operation of the first comparator circuit may adversely affect the linearity of the sweep circuit.

It has been candidly assumed that the actual function to be quantized remains at some fixed value for the duration of the main sweep. This implies one of two things; that a clamping circuit be used which will clamp the input waveform to its value at a certain instant of time and hold it fixed for a period of 400 microseconds, or that the input data be limited in frequency so that changes in amplitude during a sampling period may be neglected. The latter case is highly undesirable.

Work has been done with clamping circuits but it is doubtful whether a satisfactory circuit exists to clamp a voltage to an accuracy of 0.1% with the proper degree of stability. It is suggested that this may be a fruitful field for investigation.

Appendixes

Appendix A. Other Comparator Circuits

It has been stated previously in the discussion of the voltage comparator circuit that many types of circuits may be used to perform voltage comparison. For a complete coverage the reader is referred to reference #4.

The action of a comparator circuit may be compared to that of closing a switch. In short, a discontinuous function is desired in which the discontinuity takes place by virtue of equality of two voltages. Though a step discontinuity is desired, in actual practice a ramp function is usually approximated. The procedure is then usually to amplify this discontinuity in slope so that it approaches a step function.

The most commonly used physical components having discontinuities in their characteristics are crystals, contact rectifiers, gas tubes, diodes, and multigrid tubes. In the problem at hand stability is of prime importance, together with resolution. The percentage resolution may be made arbitrarily high by raising the voltage range over which comparison takes place to a sufficiently high value. Physical limitations in the proposed circuit limit the range of voltage to 100 volts. When the range is limited to 100 volts, resolution must be 0.1 volt. This eliminates contact rectifiers because their discontinuity is indefinite over a relatively broad range. The break point or change in slope of multigrid tubes operated about their cutoff voltage is considerably

less sharp than that for a typical diode. The triode has the advantage that it provides its own amplification and presents a constant input impedance over its break characteristic, but these considerations are of secondary importance in this application.

Though gas tubes exhibit extremely sharp break characteristics when going into conduction, the conduction point is extremely unstable by the standards chosen.

The choice to be made was between the crystal and the diode selectors. While the crystal has the advantage of having a sharper break in its characteristic, it has three main disadvantages. These are wide variation from unit to unit, high ambient temperature sensitivity, and low maximum operating voltages. This latter point alone is sufficient to preclude the use of crystals in the application proposed.

If the temperature sensitivity and operating voltage were to be improved for the germanium crystal, it would be advantageous to employ it in place of the diode used. Very little change in the circuit chosen would be required to effect the substitution.

Appendix B. Crossover Coincidence

The basic problem connected with the so-called crossover points, (i.e. points at which the fine count jumps from 0 to 32), has been discussed in connection with the time amplifier block diagram of Fig.9. A circuit diagram is here presented to further illustrate the proposed solution to the problem. This appears in Fig.13 together with waveforms illustrating the time relationships involved.

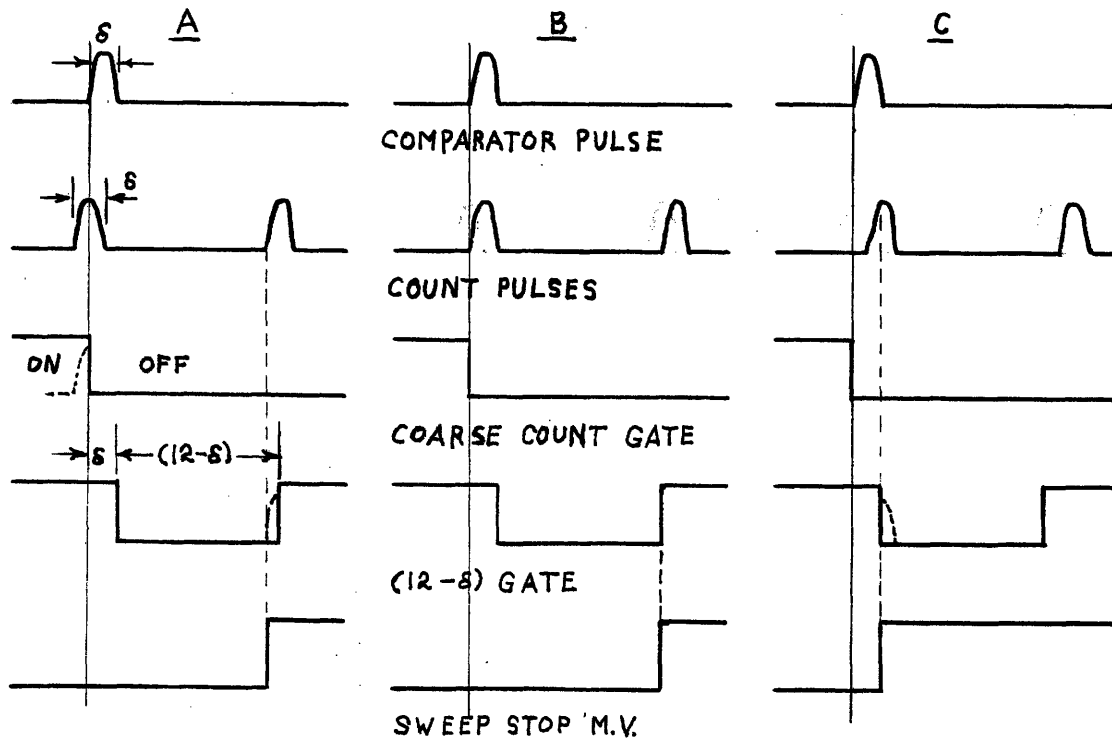
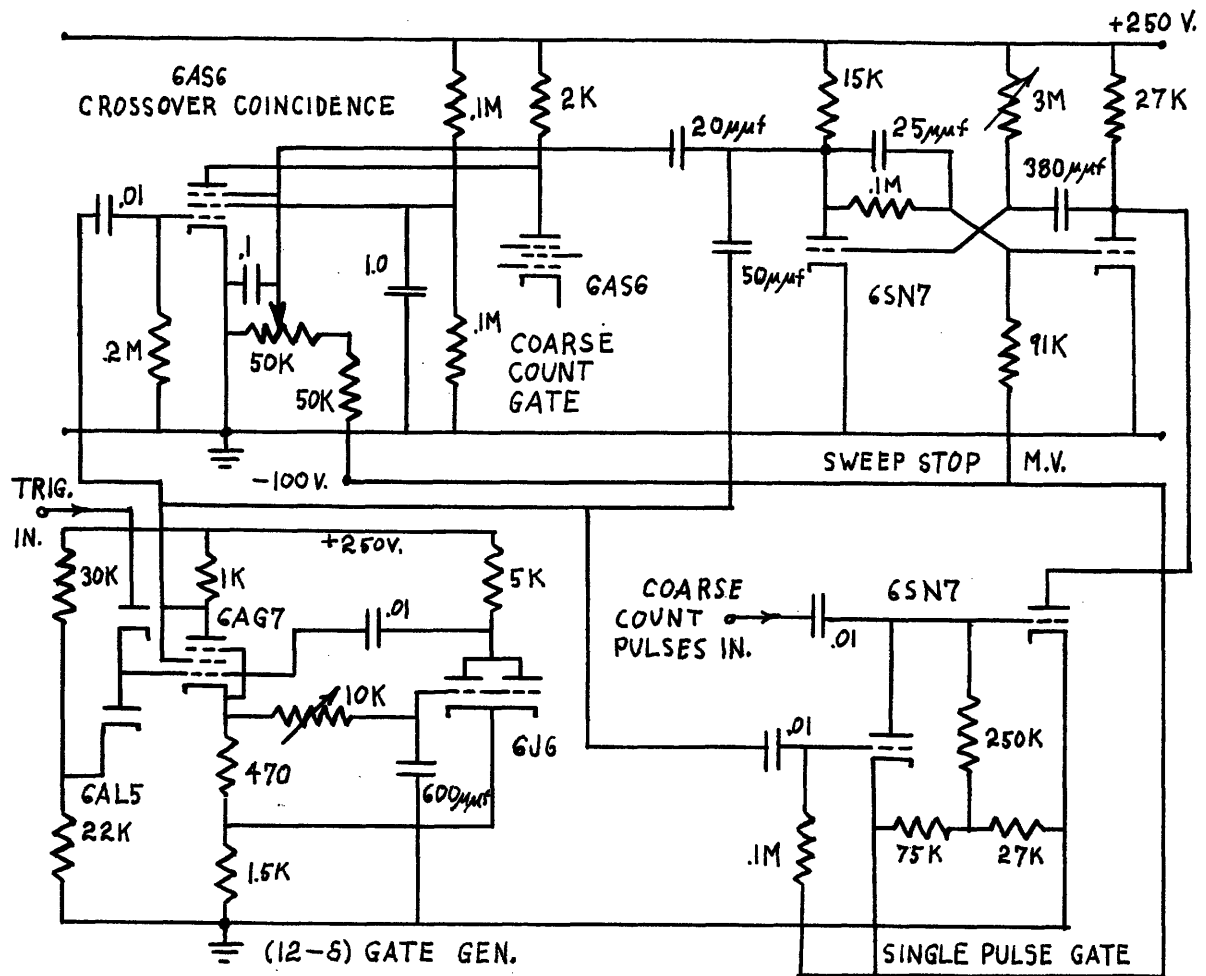


FIG. 13. CROSSOVER COINCIDENCE CIRCUIT

The three modes of operation are illustrated by the waveforms showing pulse positions A, B, and C with respect to the gate circuits. If the coarse count pulse occurs in position A, half the pulse gets through the coarse count gate and one count is added to the coarse count. The first half of the next coarse count pulse is gated through the Single Pulse Gate to trigger the Sweep Stop Multivibrator. This will result in one coarse count and no fine count giving a total count of 32, since the coarse count is multiplied by 32.

In case B, the coarse count pulse does not appear in the coarse count and no pulse is gated through the Single Pulse Gate to trigger the Sweep Stop Multivibrator. In this case the trailing edge of the negative going gate from the (12 - δ) Gate Generator triggers the Sweep Stop Multivibrator through a differentiating network. This would give a coarse count of 0 and a fine count of 0, but the Crossover Coincidence Circuit in this instance produces a coarse count pulse to make the coarse count 32.

In the case of pulse position C, the coarse count gate receives no pulses before the gate is closed. The trailing edge of the coarse count pulse triggers the Sweep Stop Multivibrator to give a fine count of 32. In each case the total count was 32. If the entire circuit is to have a resolution of one count in 1000 it is essential that pulse width δ be less than one count width, .375 microseconds.

Appendix C. Time Amplifier Test Circuit

The circuit used to produce the triggers required to trigger on the

Sweep Start and Sweep Stop Multivibrators is reproduced in Fig. 14.

It consists of a sine wave synchronized astable multivibrator to set the timing, and two blocking oscillators to furnish the triggers. An isolating cathode follower is also provided to trigger one of the blocking oscillators.

The astable multivibrator V1 generates a highly unsymmetrical rectangular waveform. The negative going wave of the narrow pulse is differentiated and applied to the blocking oscillator V2 which is held normally cut off. This blocking oscillator supplies a trigger to the cathode of the Sweep Stop Multivibrator at the time of the trailing edge of the narrow pulse from V1.

The positive going narrow pulse from the astable multivibrator is applied to an integrating circuit to create a positive going sweep for the duration of the narrow pulse. This positive sweep is applied to the blocking oscillator V3b by means of the cathode follower V3a. This blocking oscillator will trigger at some point on the sweep depending on the setting of its grid bias potentiometer. Its triggering point may then be varied with respect to the triggering point of the blocking oscillator V2 which always triggers at the end of the narrow pulse. The trigger generated in V3b is fed to the cathode of the Sweep Start Multivibrator. In this manner two pulses with a variable time between them are generated.

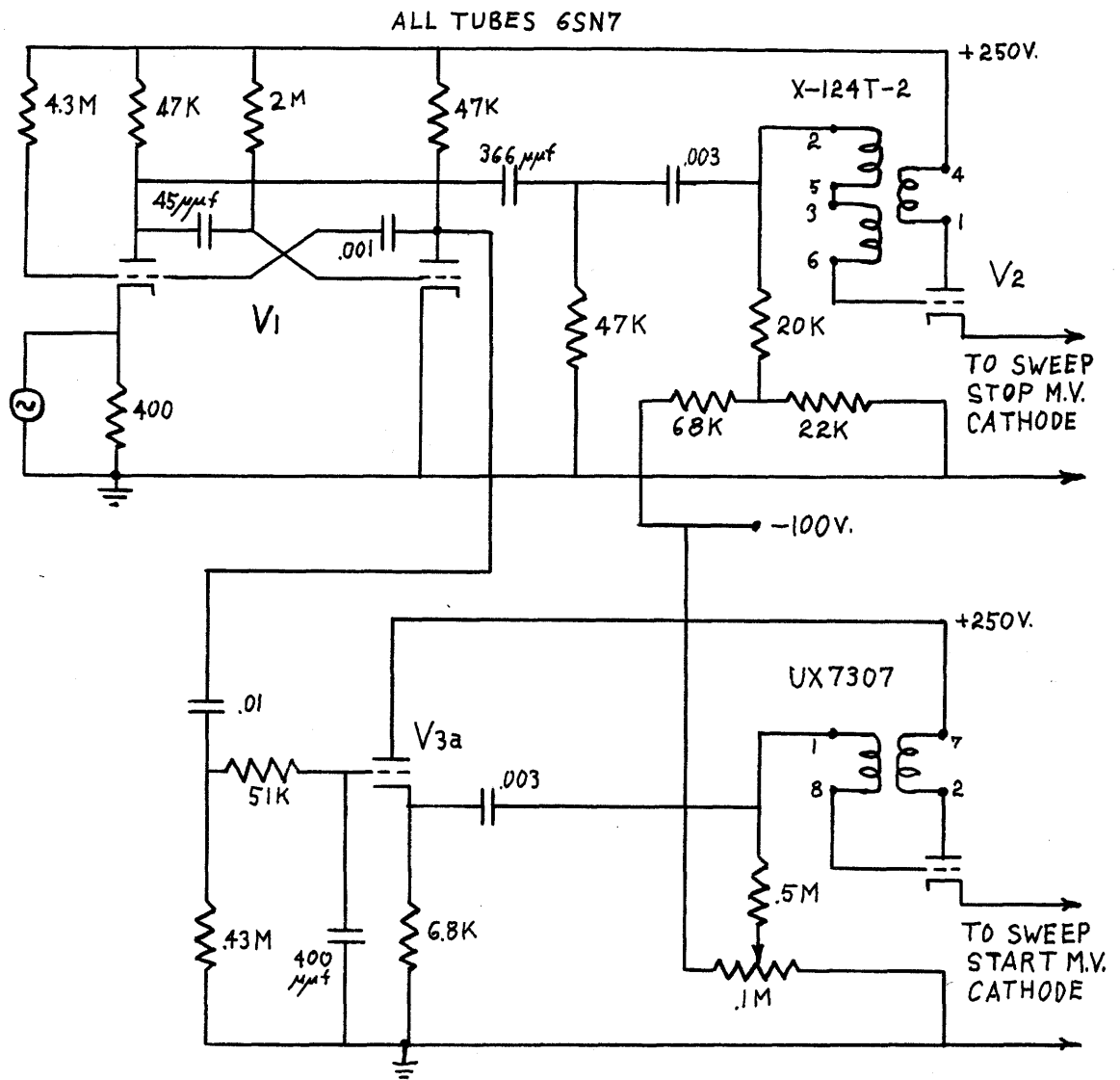


FIG. 14. TEST CIRCUIT FOR TIME AMPLIFIER

BIBLIOGRAPHY

1. Smith, B.D. P.C.M. Method, Meteor Report No. 23, MIT Guided Missiles Program, Dec. 1948.
2. Sears, R.W. "Electron Beam Deflection Tube For P.C.M.," Bell System Technical Journal, Jan. 1948.
3. Glasoe and Lebaeqz, Pulse Generators, Vol. 5 Radiation Laboratory Series, McGraw-Hill, 1948.
4. Chance, B.; et al, Waveforms, Vol. 19 Radiation Laboratory Series, McGraw-Hill, 1949.
5. Williams, F.C. and Moody, N.F., Some Remarks on Ranging Circuits, Linear Time Base Generators, and Time Discriminators, I.E.E. Convention Paper, Mar. 1946, p.13.
6. Johnson, E.C., An Electronic Simulator for Nonlinear Servomechanisms, MIT EE MS Thesis, 1949.
7. Sallen, R.P., A Method of P.C.M., MIT EE SM Thesis, 1949